Near-Infrared Adaptive Optics Spectroscopy of Binary Brown Dwarf HD 130948B and C[1]

Miwa Goto[2], Naoto Kobayashi, Hiroshi Terada,
Wolfgang Gaessler, Tomio Kanzawa
Subaru Telescope, 650 North A'ohoku Place, Hilo, HI 96720
mgoto@duke.ifa.hawaii.edu

Hideki Takami, Naruhisa Takato, Yutaka Hayano,
Yukiko Kamata, Masanori Iye
National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

D. J. Saint-Jacques
Départment de physique, Université de Montréal, Montréal (Québec), Canada, H3C 3J7
and

A. T. Tokunaga, D. Potter, M. Cushing
Institute for Astronomy, University of Hawaii, Woodlawn Dr., Honolulu, HI 96822

ABSTRACT

We present near-infrared spectroscopy of low-mass companions in a nearby triple system HD 130948 (Gliese 564, HR 5534). Adaptive optics on the Subaru Telescope allowed spectroscopy of the individual components of the 0.″13 binary system. Based on a direct comparison with a series of template spectra, we determined the spectral types of HD 130948B and C to be L4 ± 1. If we take the young age of the primary star into account (0.3–0.8 Gyr), HD 130948B and C most likely are a binary brown dwarf system.

Subject headings: stars: low-mass, brown — stars: binaries: close — stars: individual (HD 130948)

1. Introduction

HD 130948 is a triple system discovered by Potter et al. (2002) using the University of Hawaii adaptive optics system (Hōkūpa'a) in the course of an imaging survey of low-mass companions to nearby young stars using the Gemini North telescope. The HD 130948 (Gliese 564, HR 5534) system consists of a G2V primary star and a binary companion at a separation of 2.″63 from the primary. The binary companions are separated by 0.″134, or 2.4 AU at a distance of 17.9 pc determined by *Hipparcos*. Potter et al. (2002) confirmed the common motion of the members of the triple system with a baseline of 7 months to reject the chance projection of background sources. By using the AO system on the Subaru Telescope, we obtained individual spectra of each component to confirm the substellar nature of the faint companions, HD 130948B and C.

[1]Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

[2]Visiting astronomer at the Institute for Astronomy, University of Hawaii

2. Observations and Data Reduction

The spectroscopic observation was made on UT 2001 May 3 using the Infrared Camera and Spectrograph (IRCS; Tokunaga et al. 1998; Kobayashi et al. 2000) with the 8.2 m Subaru Telescope in conjunction with its adaptive optics (AO) system (Takami et al. 1998; Gaessler et al. 2002). The Subaru AO system, which is equipped with a 36-element curvature sensor, is installed at the front end of the telescope Cassegrain port. A medium-resolution grism was used with a $0\farcs10$ slit in the 22 mas camera section of the IRCS to provide spectra with a resolving power of 800–1000 in the H and K bands. HD 130948A was used as the reference source for the AO system. The slit was put along the position angle of HD 130948B and C to cover them simultaneously. The spectra were recorded by nodding the telescope by $1''$ along the slit to subtract the sky emission. The total on-source integration time was 1200 s in both the H and K bands. A nearby B8V star HD 164352 was observed as a spectroscopic standard at similar airmass. The standard star is bright enough to give nearly the same AO correction as for HD 130948A. The spectroscopic flat field was obtained at the end of the night with a halogen lamp. The seeing was $0\farcs4$–$0\farcs5$ at 2.2 μm throughout the observing period.

Because of the close proximity and the large difference in luminosity between the primary and companions, the sky background in the spectrum is affected by the gradient in the wing of the point-spread function (PSF) of the bright primary. After a pair subtraction of the sky the residual background slope was removed by interpolating the background on both sides of the companion.

We obtained the one-dimensional spectra using the IRAF[3] aperture extraction package after flat-fielding and bad-pixel correction. Special attention was paid to the adjustment of the aperture width. Figure 1 shows crosscuts of the observed spectrogram in the spatial direction with an overlay of the standard star profile normalized at the peak of each object. The FWHM of a standard star is as sharp as $0\farcs1$ and $0\farcs08$ in the H and K bands, respectively. However, the intensity of the first diffraction ring is significant. The separation between the centroid and the peak of the first diffraction ring for an ideal diffraction-limited image of the 8.2 m circular opening should be $0\farcs07$ and $0\farcs09$ in the H and K bands, respectively. This is similar to the angular separation of $0\farcs13$ between HD 130948B and C. Consequently, the energy of HD 130948B in the first ring as well as the halo overlaps with HD 130948C. This may produce similar spectral signatures in both components that may be misleading.

We calculated the contamination expected with the standard star PSF. The flux contamination of C by B within the 3 pixel ($0\farcs067$) aperture width is 25% and 22% in the H and K bands, respectively. The contamination of B by C is <20%. The extraction aperture width of the standard star is set to the same as that of the objects. To provide the correct weight to the optimal extraction method (Horne 1986), the statistical error in the 2D spectrogram image is calculated by combining the readout noise and the shot noise from the sky emission and PSF spillover from the primary. The wavelength calibration was performed by fitting about 20 emission lines of the argon arc lamp of the Subaru Telescope calibration unit with a linear function.

The intrinsic stellar lines in the standard star spectra, which are mostly atomic hydrogen lines, were difficult to remove because of their superposition with the telluric absorption lines. Only six of them at 1.588 μm (Br10), 1.641 μm (Br8), 1.681 μm (Br7), 1.737 μm (Br6), 2.166 μm (Brγ), and 2.374 μm (Pf20) were fit with a Lorentzian profile and subtracted before division. The small discrepancy in the airmass between the standard and the object was corrected by rescaling the standard star spectra according to Beer's law. Rough flux calibration relative to the standard star was made in each band by assuming the intrinsic spectra of a B8V star is represented by a Planck function of $T_{\rm eff} = 10700$ K (Tokunaga 2000).

3. Result and Discussion

3.1. Spectral Type of HD 130948B and C

To determine the spectral types of HD 130948B and C, we compared the object spectra with template spectra of low-mass stars published by Reid

[3]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

et al. (2001), Geballe et al. (2002), Leggett et al. (2000), and Leggett et al. (2001). We found none of the template spectra match well with the object spectra. The continua of the object spectra were too steep to be a low-mass star, though the low-mass nature is apparent in the strong absorption of H_2O at both ends of the H and K bands. We concluded that the continuum slope was affected by the AO correction. Not only a little offset from a narrow slit, but also slight difference in seeing can result in the variation of the continuum slope because of the sensitive wavelength dependency of the encircled energy on the AO performance (M. Goto et al., in preparation). The variation of the continuum slope from exposure to exposure was sometimes as much as 10% per 0.1 μm. Most of the time the difference was well represented by a simple linear function.

Because of the uncertainty of the continuum slope, we had to correct the object spectra by multiplying a linear function before comparison with templates. The strength of H_2O absorption increases with spectral type, and the spectral change between any two spectral types is not a linear function. In other words, we cannot convert the spectrum of an L1 star to an L8 star by just multiplying a linear function. Therefore, in principle, we can determine the spectral type of an object uniquely by matching both the H_2O absorption with a template spectrum, even if we have a linear continuum slope uncertainty.

First, we assumed HD 130948B (or C) is a certain spectral type, and estimated how much linear continuum correction is required to best match the object spectrum with the template spectrum of the assumed spectral type. We calculated the cross-correlation between the object spectrum and the template spectrum as a function of the steepness of the applied linear function correction. The slope of the function is determined so that the cross-correlation between the corrected object spectrum and the template spectrum is highest. We repeated this procedure for each spectral type from L1 to L8.

Second, we investigated how well it matched each spectral type from L1 to L8. The value of the cross correlation calculated above peaks at L3–L5 in the H band and at L1–L5 in the K band. Considering the simultaneous match in the H and K bands, we conclude both HD 130498B and C agree best with the template for L4 $\pm$ 1. This is consistent with the spectral type of L2 $\pm$ 2 determined independently by Potter et al. (2002).

The final object spectra after correction are shown in Figure 2 with overlay of the best-matched template spectra, 2MASSW J0036+18 (L4). The spectra were binned by 2 pixels along the dispersion direction. The spectra of HD 130948B and C turn out to be very similar to each other in detail and are almost twins, except that HD 130948B is 0.2–0.3 mag brighter than C. The deep absorption bandhead of the CO molecule at 2.3–2.4 μm is conspicuous. The presence of absorption lines of Na I (2.209 μm) and K I (1.516 μm) supports the idea that these are low mass stars. The absorption band of CH_4 is not seen. This is in good agreement with the conclusion that HD 130948B and C are not later than mid L-type stars. A series of the "unidentified" absorption features reported by Reid et al. (2001) at 1.58, 1.613, and 1.627 μm can be all attributed to the FeH molecule (Wallace & Hinkle 2001). Ca I lines noted by Jones et al. (1994) and Tinney, Mould, & Reid (1993) are marked in the figures.

3.2. Mass of HD 130948B and C

The range of spectral types derived above corresponds to an effective temperature of $T_{\rm eff}$ = 1900 ± 75 (Leggett et al. 2001). On the basis of moderate X-ray activity, a fast rotation period ($\sim$ 7.8 days), and photospheric lithium abundance, the age of the primary should be 0.6 $\pm$ 0.2 Gyr (Gaidos 1998; Gaidos, Henry, & Henry 2000). On the other hand K. Fuhrmann (2001, private communication) finds that HD 130948A may be a member of the Ursa Major Stream, which has estimated age of 0.3 to 0.65 Gyr (Giannuzzi 1979; Soderblom & Mayor 1993; Palouš & Hauck 1986; Chen et al. 1997).

Figure 3 is a reproduction of the evolutionary tracks of various low-mass stars of solar metallicity calculated by Baraffe et al. (1998). Regardless of the uncertainty in the age determination of the HD 130948 system, the estimated masses for HD 130948B and C are under the sustainable hydrogen burning limit, 0.075 $M_\odot$ for solar metallicity, for both companions, and the most likely mass of the object is 0.040–0.065 $M_\odot$.

4. Summary

We have presented moderate-resolution near-infrared spectra of the close binary companions recently discovered near HD 130948. The general spectral features of the companions, HD 130948B and C, are very similar. Based on a direct comparison with template spectra of low-mass stars, we have determined the spectral type of HD 130948B and C is L4 $\pm$ 1. This is consistent with the result of Potter et al. (2002), who found a spectral type of L2 $\pm$ 2 for the binary companions. If we take the young age of the primary star (0.3–0.8 Gyr) into account, then HD 130948B and C are binary brown dwarfs.

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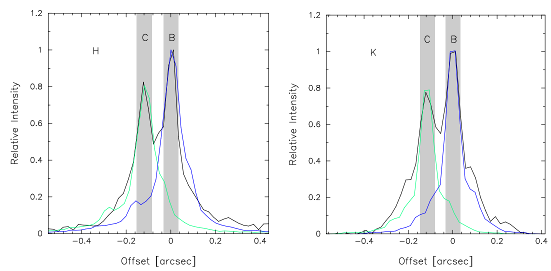
Fig. 1.— Cross-section of the spectrogram across the slit length in the H and K bands with an overlay showing the spatial profile of the standard star. The standard star profile is registered to the position of each component and normalized at the peak of the object profile. The shaded areas represent the size of the aperture that the one-dimensional spectra are extracted from.

Fig. 2.— H- and K-band spectra of HD 130948B and C normalized to the flux of HD 130948B at 1.65 and 2.20 μm, respectively. The overlay is the best-matched template spectrum, 2MASSW J0036+18 (L4).

Fig. 3.— The tracks of effective temperature for low-mass stars as a function of age (Baraffe et al. 1998). The effective temperature range for HD 130948B and C is indicated by the rectangular enclosure, along with the age determination uncertainty.



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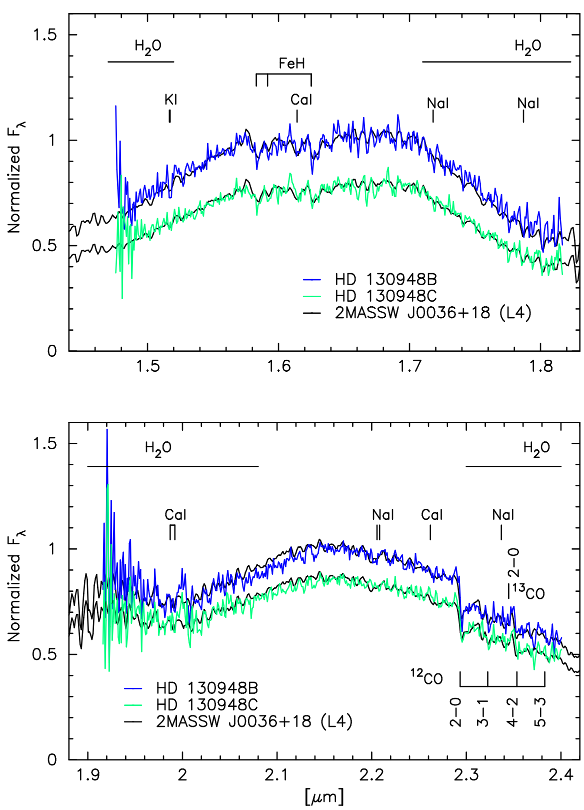

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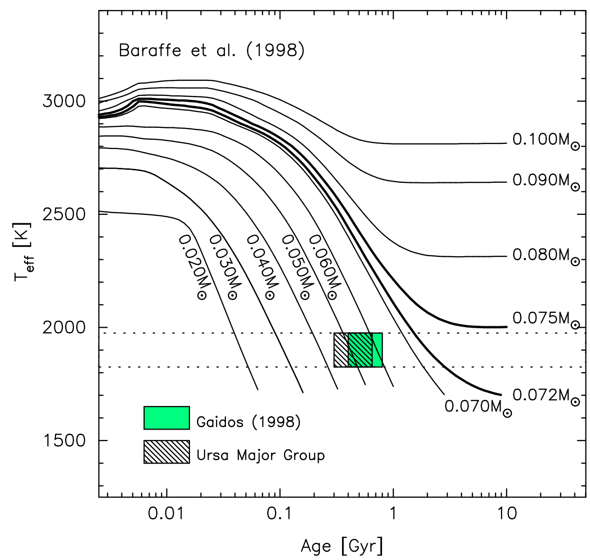

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